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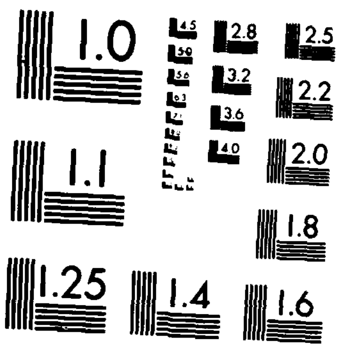

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Final Report: Adaptive Assessment of Spatial Abilities

Isaac I. Bejar

Educational Testing Service

Princeton, NJ 08541

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This report summarizes the results of an 18-month contract entitled Adaptive Assessment of Spatial Ability. The project was focused on the psychometric and technological feasibility of adaptive testing systems of a procedural as opposed to declarative nature. That is, adaptive testing systems where items are generated as needed rather than explicitly retrieved from a database. To investigate the feasibility of such an approach to adaptive testing data was collected from high school students on two types of spatial items, three-dimensional cubes and hidden figure items. The analysis of the three-dimensional cubes focused on the fit of the simplest possible item response model capable of modeling response time; the analysis of the hidden figure item focused on the feasibility of generating item from an algorithm in such a way that the psychometric characteristics of the generated items were predictable. The results for the three-dimensional cube

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items suggested that angular disparity can be used effectively to control the difficulty of true items but this was not the case for false items. That is, true and false items appear to measure different aspects of performance and as a result a multidimensional item response model may be necessary to fully account for performance on even fairly simple spatial items such as three-dimensional cubes. The analysis of the hidden figure items showed that an item generation algorithm can be formulated to produce items of similar psychometric characteristics. The practical and theoretical implication of the results are discussed.

Abstract

This report summarizes the results of an 18-month contract entitled Adaptive Assessment of Spatial Ability. The project was focused on the psychometric and technological feasibility of adaptive testing systems of a procedural as opposed to declarative nature. That is, adaptive testing systems where items are generated as needed rather than explicitly retrieved from a database. To investigate the feasibility of such an approach to adaptive testing data was collected from high school students on two types of spatial items, three-dimensional cubes and hidden figure items. The analysis of the three-dimensional cubes focused on the fit of the simplest possible item response model capable of modeling response time; the analysis of the hidden figure item focused on the feasibility of generating item from an algorithm in such a way that the psychometric characteristics of the generated items were predictable. The results for the three-dimensional cube items suggested that angular disparity can be used effectively to control the difficulty of true items but this was not the case for false items. That is, true and false items appear to measure different aspects of performance and as a result a multidimensional item response model may be necessary to fully account for performance on even fairly simple spatial items such as three-dimensional cubes. The analysis of the hidden figure items showed that an item generation algorithm can be formulated to produce items of similar psychometric characteristics. The practical and theoretical implication of the results are discussed.

Final Report: Adaptive Assessment of Spatial Abilities

Isaac I. Bejar

As the title of this project suggests, the aim of this research is to study the feasibility and requirements of adaptive testing for spatial ability. However, although the content of the research has been spatial abilities, the goal is in fact broader, namely to develop a methodology for what might be called second-generation adaptive testing that will be applicable not only to spatial but to other abilities as well.

First-generation adaptive testing methodology is well known and can be summarized as follows: Given a pool of items calibrated on a common scale, choose the set of items that is maximally informative for a given examinee. This methodology has now reached the point where it is a marketable product, and while there may still exist a need to do research on refinements of the methodology, the basic structure of the paradigm is well set.

A characteristic of first-generation adaptive testing is its **declarative** nature. That is, each item in the pool must be stored explicitly in a database along with its psychometric parameters with respect to some item response model. A natural elaboration of this approach was investigated in this project. That is, instead of our explicitly enumerating all the items, we investigated the idea of constructing algorithms that generate the items with control of their psychometric characteristics. Rather than calibrating specific items, we calibrated the procedures that generate the items. In short, the elaboration moves from a declarative approach to a **procedural** one.

Clearly, procedural adaptive testing involves more than psychometrics, since the encoding of items into procedures requires very specific knowledge about the determinants of item performance. It is precisely this requirement that offers some hope of improving the validational status of scores from an adaptive testing procedure. The current approach to adaptive testing improvement in validity is limited to the improvement accruing from more precise measurement. There is hope that the next generation in adaptive testing will improve the validational status of test-score interpretations by continually submitting to testing the theory of item performance embedded in the item-generation algorithm. As a result of that continual challenge, the theory will either be confirmed or revised, and it is very likely that in that process we will learn much about the psychological underpinnings of performance on the test.

The calibration of a procedure consists of item linking those determinants of performance to a psychometric scale. The details of how this is done vary with the item type. In this project, we experimented with a three-dimensional mental rotation item and a hidden-figure item type.

The Psychometrics of Three-dimensional Mental Rotation

An example of this item type is shown in Figure 1. This item type was chosen because there exists a large body of literature (cf., Corballis, 1982) establishing that an angular disparity between the two figures largely determines performance. Moreover, it appears that there are fairly stable and consistent gender differences in performance on mental-rotation tasks (Linn and Petersen, 1985).

The approach taken was to examine the simplest possible psychometric model of an 80-item test based on figures such as those in Figure 1. (There were eight basic items presented at five angles in their true and false version.) The items were presented at angular disparities of 20, 60, 100, 140, and 180 in order to establish the relationship between angular disparity and difficulty. The simplest model that can be fitted to these data makes the following predictions:

- The relationship between difficulty and angular disparity is linear.

- The slope of that relationship is constant at different response times.

- The intercept of the relationship is solely a function of response time.

This model is an extension of the dichotomous item-response model to the case in which the response is response time (see Samejima, 1973). Thus, to score an examinee, we simply note the response time to an item with a certain angular disparity. Together, the angular disparity and response time determine the corresponding difficulty, and they allow us to obtain an ability score for this examinee.

Figure 2 shows the result of a calibration for a typical item based on the responses of nearly 200 high school students. As can be seen, there are some departures from the predictions although, in general, the fit for this item is good. The major deviation from linearity occurred at 100 degrees. Also, beyond 5 seconds, a tendency towards a quadratic relationship between difficulty and angular disparity emerges, a situation which suggests that beyond a certain moment in time different strategies come into play.

The results for the false items are quite different, in that angular disparity does not seem to control performance as it does for the true items. That is, the false items seem to tap the decision aspect of performance, while the true items are tapping the mental rotation aspect. Figure 3 shows the corresponding data.

The results of this study are presented in more detail in The Psychometrics of Mental Rotation (RR-86-19). It is concluded that in

Figure 1

Sample True and False Three-dimensional Rotation Items

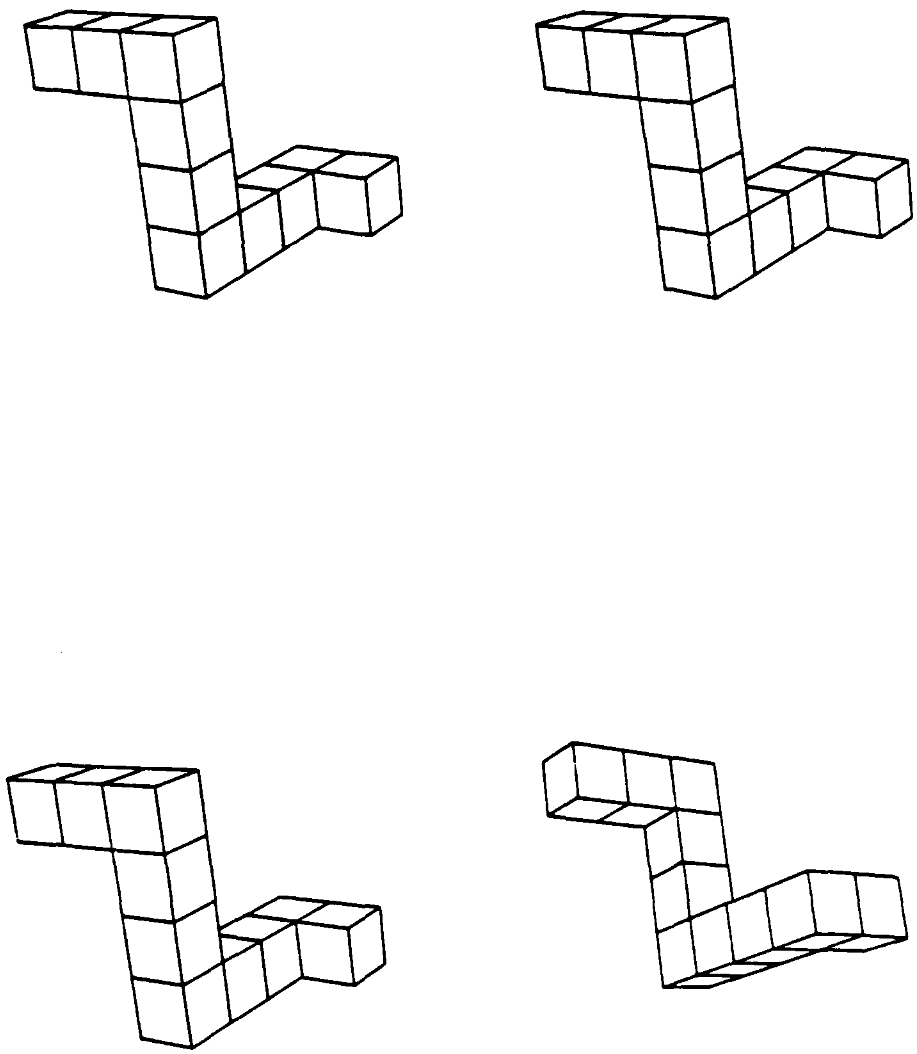


Figure 2

Relationship Between Psychometric Difficulty and Angular Disparity

After 3, 4, 5, 6 and 7 Seconds for True Version of Item E1

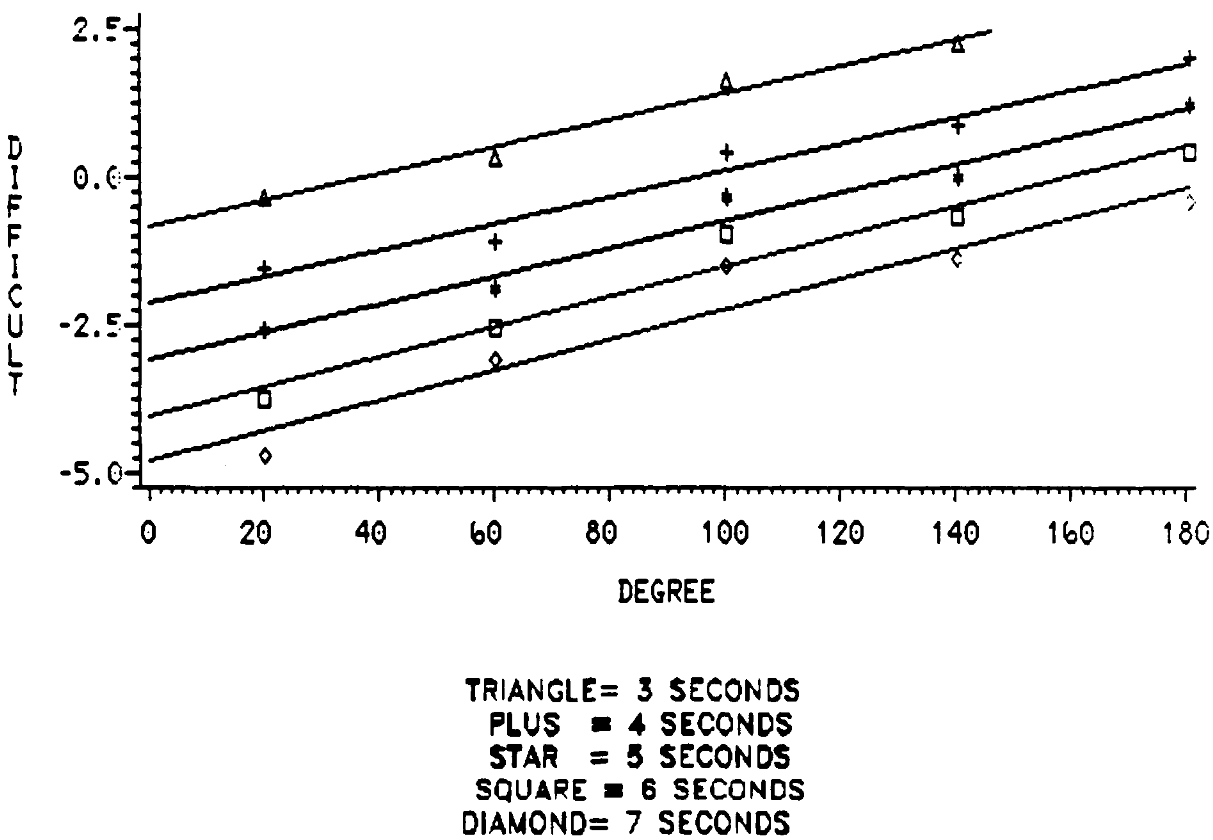
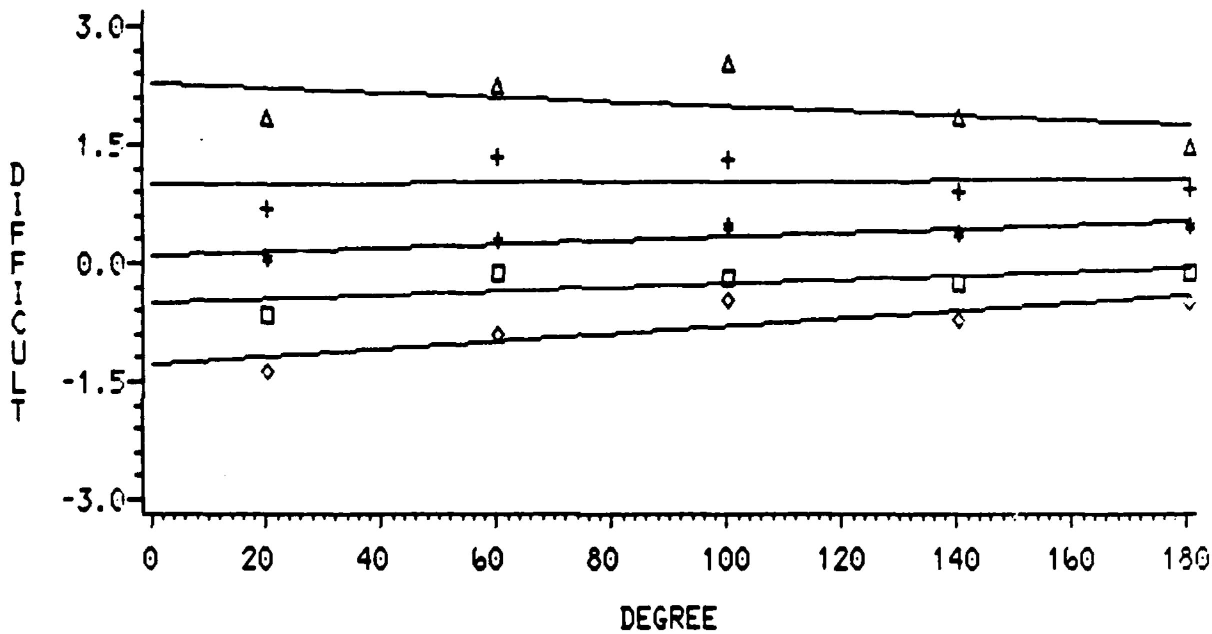


Figure 3

Relationship Between Psychometric Difficulty and Angular Disparity

After 3, 4, 5, 6 and 7 Seconds for False Version of Item E1



TRIANGLE= 3 SECONDS
PLUS = 4 SECONDS
STAR = 5 SECONDS
SQUARE = 6 SECONDS
DIAMOND= 7 SECONDS

practical applications, the appropriate psychometric model for this item type is a two-dimensional one. However, in a computerized testing environment, it may be unnecessary to embellish the psychometric model to account for curvilinear relationships between angular disparity and difficulty. Instead, in the tailoring of the test we chose items for an individual in such a way that a response is given within, say, 5 seconds. Such a tailoring strategy may have other benefits as well.

Hidden Figure Items

Unlike the mental-rotation items, for which the determinants of performance are fairly well known, very little is known about the determinants of performance in hidden-figure items. Therefore, our first task was to discover a psychometrically useful representation of the item. There were two important constraints on that representation. One was that it should provide a description of the item that captures the "psychometric essence" of the items. Ideally, that representation should be psychologically motivated, that is, motivated by previous research on the processes and mental models that account for performance on this type of cognitive task. Unfortunately, for the hidden-figure item, it was not possible to locate the relevant research. In addition, the representation should lend itself to generating items that had the same underlying representation but a different visual realization. For convenience, we call the items generated in this fashion clones. Figure 4 shows a pair of clones.

The chosen representation is a matrix consisting of counts indicating how close the target figure appears at each possible position in the larger pattern and was based on the Hough transform (Mayhew and Frisby, 1984), an artificial intelligence technique used in object recognition. We tested the psychometric validity of this representation by implementing a computer program capable of generating psychometric clones and then by comparing their psychometric characteristics on the basis of responses from high school students.

The item generation algorithm takes the matrix of counts together with a small pattern and tries to create a large pattern that matches the matrix. The generation process is simplified by the fact that patterns only contain horizontal, vertical, and 45 degree lines between nodes. The basic idea is to start with a large pattern including all the possible lines and remove lines until the matching algorithm produces a matrix that equals the input matrix.

The results demonstrated that the clones behaved as such in terms of their difficulty as well as distribution of response times. Figure 5 shows the relationship between the logit for proportion correct and for pairs of clones as well as the corresponding mean response time. Figure 6 shows the cumulative response times for two clones. It can be seen they are very similar, and this was true for the other items as well. The results of this experiment appear in more detail in Analysis and Generation of Hidden Figure Items: A Cognitive Approach to Psychometric Modeling (RR-86-20).

Figure 4

Sample Hidden Figure Items Clones

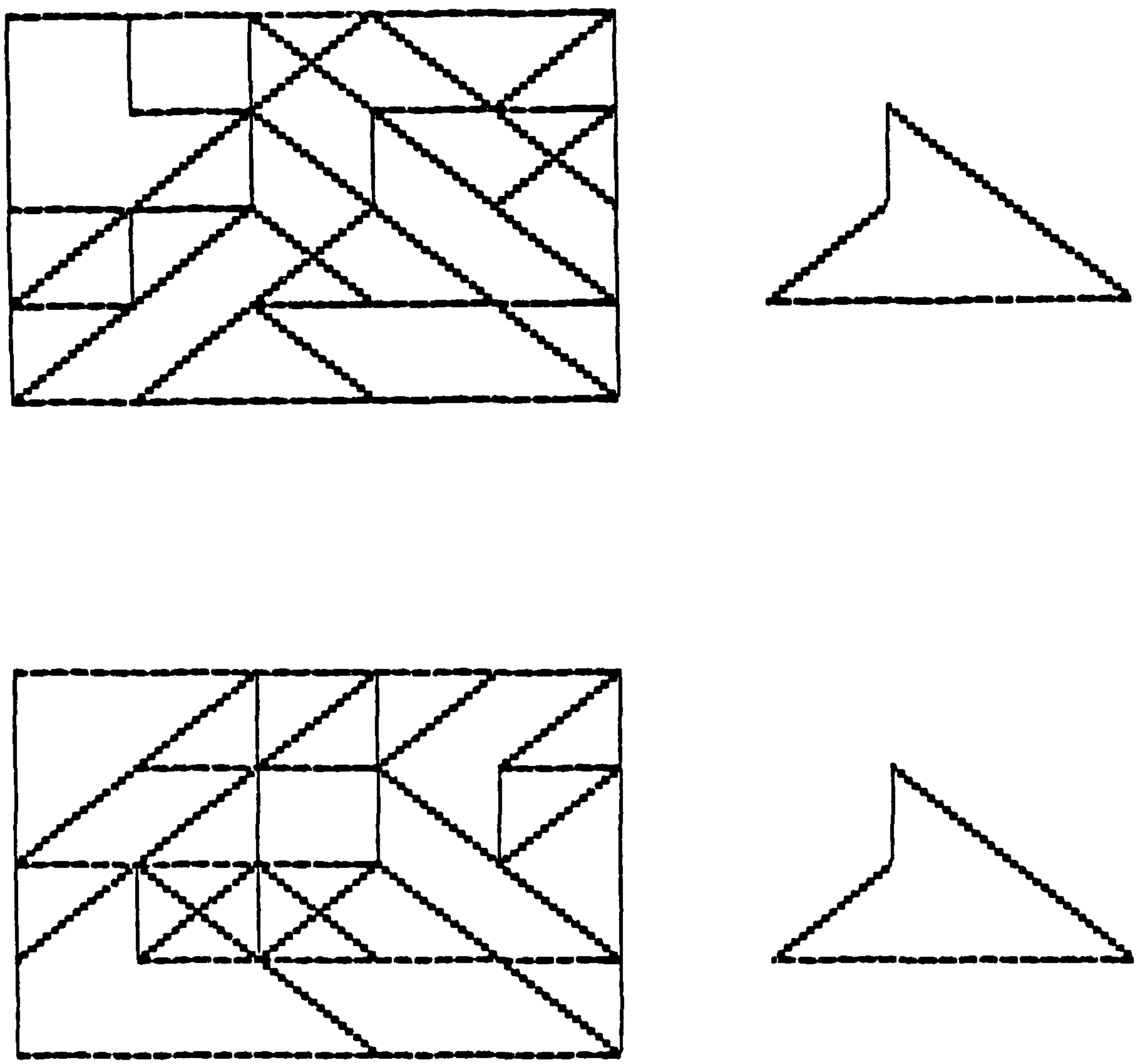
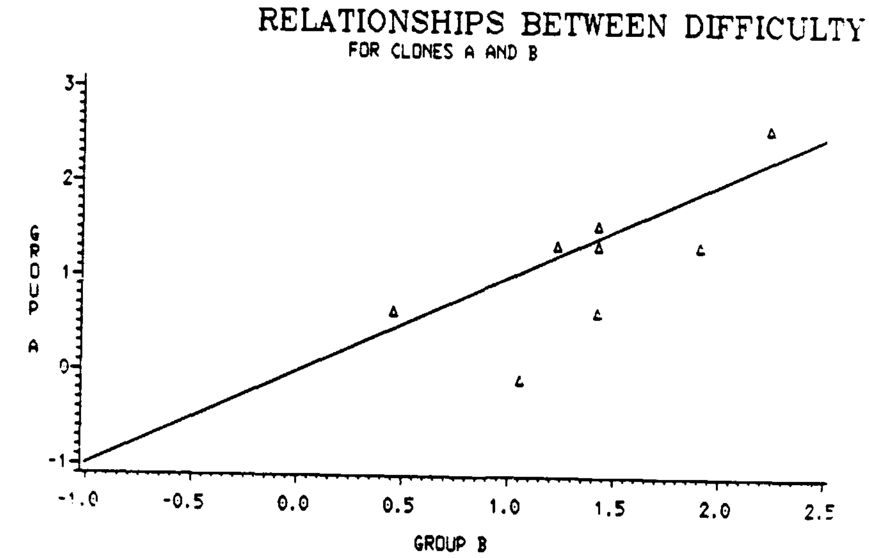


Figure 5

Relationship Between Accuracy and Latency for Hidden Figure Clones



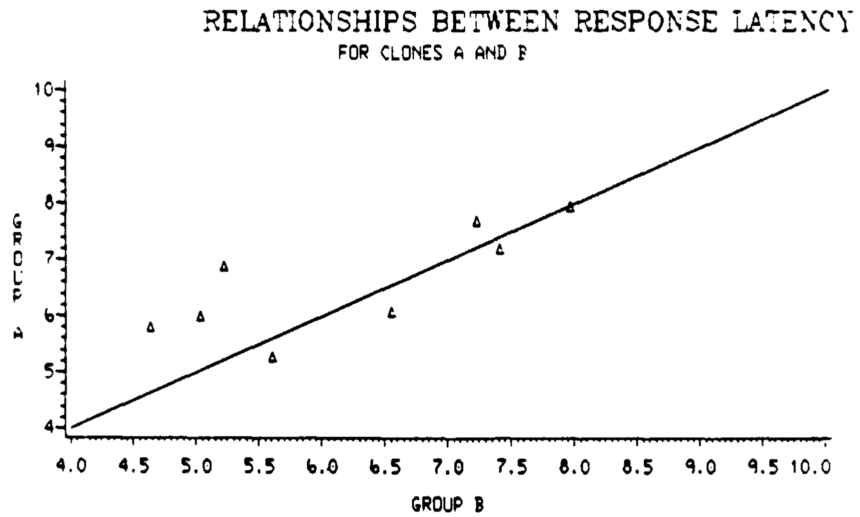
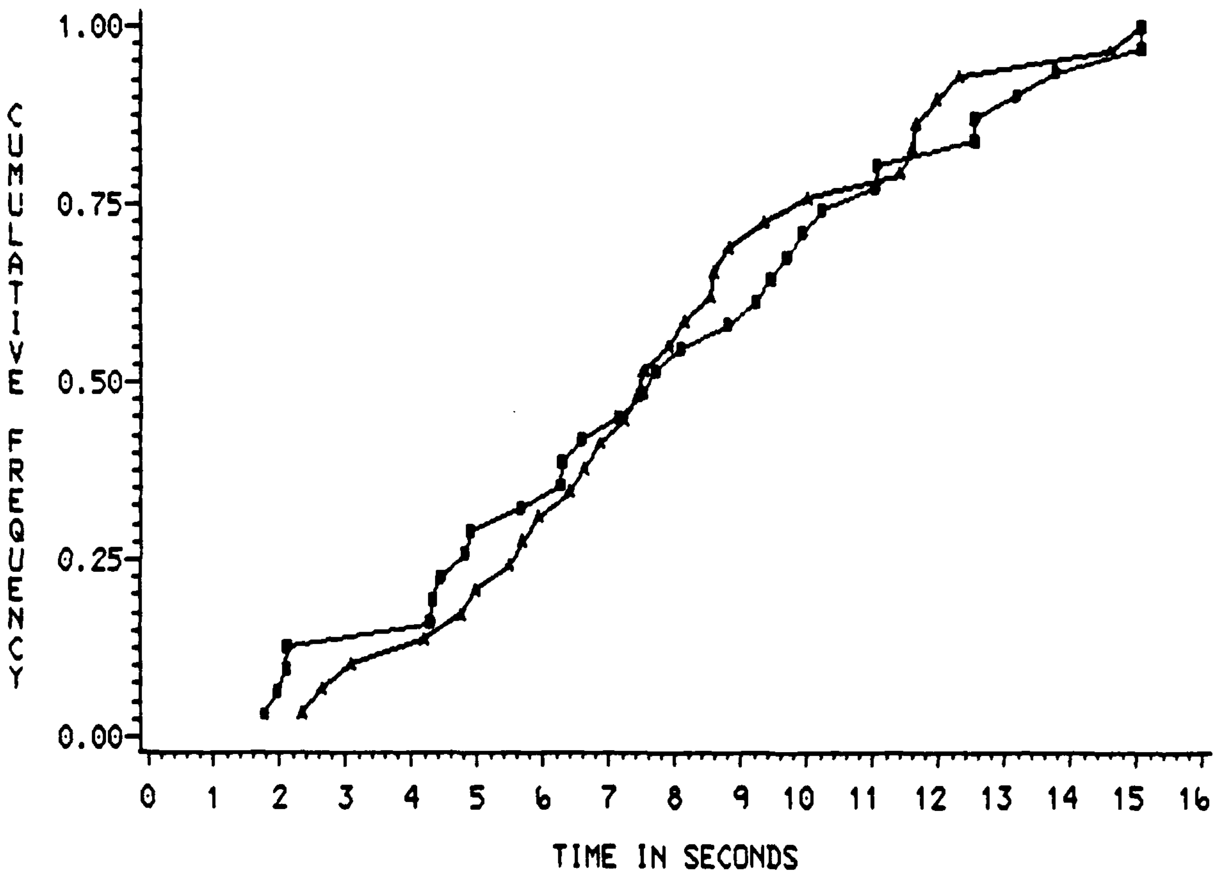


Figure 6

Cummulative Frequency Distribution of Response Times for Two Clones



Summary

The choice of item types in this study was not accidental: they were chosen to maximize the chance of a positive demonstration of what we have called "procedural adaptive testing." The essential characteristic of procedural adaptive testing is that, unlike "conventional" adaptive testing, all the items and their associated item parameter estimates need not be stored ahead of time in a database. Instead, through a design incorporating the major determinants of performance on that item, data are collected to determine the relationship between design and psychometric parameters. This simple distinction, however, has important ramifications.

At a practical level, procedural adaptive testing is likely to be more economical since it avoids the need to calibrate a large number of items. This economy may prove advantageous even in paper-and-pencil tests by facilitating the creation of a priori parallel forms and, in general, by better controlling the psychometric characteristics of the items that are placed on the test. (In fact, the item-generation program developed for the hidden-figure item has been used in the development of a Navy pilot test.)

However, the most important implication of procedural adaptive testing may not be its practical value but the constraint that it imposes on the psychometrician. It is no longer sufficient to gather, calibrate, and link items--as if these tasks were not demanding enough. To implement a procedural adaptive test, it is *also necessary to have a theory of* item performance at a level of specificity that new items can be produced on-line and under computer control. These are not trivial requirements, especially in verbal domains. Thus, in attempting to fulfill this requirement it will be necessary to gather documentation of psychological research related to performance on the item type in question, and if that knowledge is not yet available, go ahead and obtain it. This process will inevitably lead to a better understanding of test scores.

Conclusions

Psychologists, from psychometric and cognitive perspectives, have been interested in spatial ability for some time. Psychometricians should clearly be credited with the discovery and initial study of "spatial abilities." But it is equally clear that cognitive psychologists deserve credit for the understanding we have today about the nature of those abilities. Having a better understanding, however, does not mean that we are more certain about how to measure spatial abilities. Just and Carpenter (1985), for example, concluded that "item and test difficulty may be major determinants of what strategies and processes will be evoked in a task." By suggesting that item and test difficulty are causes, rather than the result of those strategies and processes, they seem to suggest that psychometric and psychological models are concerned with different phenomena. The alternative view is that not only are both models attempting to explain different manifestations of the same phenomena, but in addition the parameters of the psychometric model ought to be explainable by the psychological theory.

Adopting this view creates the potential for measurement instruments that are both theoretically and psychometrically sound. Although this project focused from the start on the development of more advanced adaptive tests, it seems that even if this had not been the case the conclusion about the need for adaptive testing would have been inescapable. If, as Just and Carpenter suggest, different strategies are invoked by items of a certain difficulty level, then it appears that a valuable contribution of adaptive testing is its preventing the use of different strategies by controlling the difficulty of items presented to the examinee. The three-dimensional rotation data collected as part of this project suggest that different strategies may emerge if an examinee has not made a decision after five seconds. In an adaptive test it would be relatively simple to select items in such a way that the response would be given within, say, five seconds. This motivation for tailoring does not negate the valuable information that may lie in the ability to choose different strategies. Rather, through better control of what a given test measures, we are likely to improve the precision and validity of test outcomes. Indeed, we may be able to detect with more certainty the presence of alternative strategies by being able to identify respondents that depart from an expected pattern of performance.

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